Ignitor and Thickness Effects on Upward Flame Spread

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Several studies,e.g. [1-5], have developed upward flame spread models which use somewhat different features. However, the models have not explicitly considered the effects of the ignitor and the thickness of material on spread. These factors have been found to be very significant in determining the potential for spread and its rate. Although theoretical results are only presented here, examples can be found in practice.

Using the flame spread model developed by Saito, Quintiere and Williams[1], the flame height(x_f) and flame spread velocity can be expressed respectively as follows:

$$x_f(t) = k_f\left[(\dot{Q}'_{ig}) + \dot{Q}'\right]^n , \tag{1}$$

where $\dot{Q}'_{ig}$ is the energy release rate per unit width of the ignitor and $\dot{Q}'$ is the corresponding value for the material

$$\dot{Q}' = \Delta H_c \left\{\dot{m}''(t)x_{po} + \int_0^t \dot{m}''(t-t_p)V_p(t_p)\,dt_p \right\} \tag{2}$$

with $\dot{m}''$,the specific burning rate; and

$$V_p(t) = \frac{1}{\tau}\left\{x_f - \left[x_{po} + \int_0^t V_p(t_p)dt_p\right]\right\} , \tag{3}$$

where $\tau = \frac{\pi}{4}k\rho c\left\{\frac{T_{ig}-T_\infty}{\dot{q}_f''}\right\}^2$. This gives an integral equation for V_p. The value x_{po} represents the ignitor flame height and the initial height of material ignited in the model. The $\dot{Q}'_{ig}$ has a fixed duration time(Δt_{ig}) following ignition(t_{ig}), and its effect is only relevant in Eq.(3) as long as the burnout time(t_b) of position x_{po} is not exceeded. In terms of step functions,η,

$$\dot{Q}'_{ig} = \eta\ (t_b(x_{po}) - t)\ \cdot\ \eta\ \{(t_{ig}+\Delta t_{ig}) - t\} \cdot \dot{Q}'_{ig}\ . \tag{4}$$

From previous work[6,7], we have an implicit formula for transient burning rate ,$\dot{m}''(t)$, representative of a thermoplastic-like material,

$$\dot{m}''(\theta)\Delta H_v = \dot{q}_f'' - \sigma T_{ig}^4 - \frac{2k}{\delta}(T_{ig}-T_\infty), \tag{5a}$$

where

$$\theta = t - t_p(x) = \frac{\delta_s^2}{6\alpha}\frac{\Delta H_v}{L}\left[\frac{\delta_{ig}-\delta}{\delta_s} - \ln\left(\frac{\delta_s-\delta}{\delta_s-\delta_{ig}}\right)\right] , \tag{5b}$$

$$\delta_s = \frac{2kL}{c(\dot{q}''_f - \sigma T_{ig}^4)} , \tag{5c}$$

and

$$\delta_{ig}(x) = \sqrt{6\alpha(t_p(x) - t_f(x))} \text{ ,where } t_f \text{ is time when the flame tip is at x.} \tag{5d}$$

The properties include k, c, ΔH_v, and $L = \Delta H_v + c(T_{ig} - T_\infty)$. For thickness, ℓ : $\rho\,\ell = \int_0^{t_b(x)} \dot{m}''(t)\,dt$

A computer program was developed to solve the integral equation(3) for this thermoplastic model. From this program, we can obtain the pyrolysis zone(x_p), the flame height(x_f), the burnout position(x_b), the burnout time(t_b), the total energy release rate($\dot{Q}'$), and flame velocity(V_p) of a material at specific time(t).

As an illustration of results, properties representation of PMMA were used : k=0.346*10^{-3} kW/mK, ρ=1180 kg/m^3, and c=2.5 kJ/kgK, L=2.7 kJ/g, ΔH_c=25 kJ/g, T_{ig}=636 K, and T_∞=300 K. The flame heat flux, $\dot{q}''_f$, was selected as 30kW/m^2. Experimental results for thick PMMA[3] serve as a benchmark for accuracy as shown in Figure 1. Adjustments in the properties could improve the agreement, but we stuck to the test properties available.

A study on the effect of thickness and the ignitor included variations of thickness (mm): 0.1, 0.5, 1, 3; ignitor duration (s) : 30, 60, 120, 480; $\dot{Q}'_{ig}$ (kW/m) : 10, 25, 50 or correspondingly x_{po} (m) : 0.2 , 0.5, 1.0. Figure 2 shows for the very thin material and low durations of the ignitor, the flame will never reach 5 m. But as these parameters are increased, propagation occurs and at faster speeds. Figure 3 shows the critical values of the parameters on propagation to 5 m. It is clear that all of these factors play a critical role in propagation. Recently, New York city had a real problem of fire spread in painted stairwells having up to 16 coats of paint. This presents a real problem relevant to the effect of material thickness, and ignitor characteristics on flame spread. Prescriptions for flame spread tests must also consider these factors.

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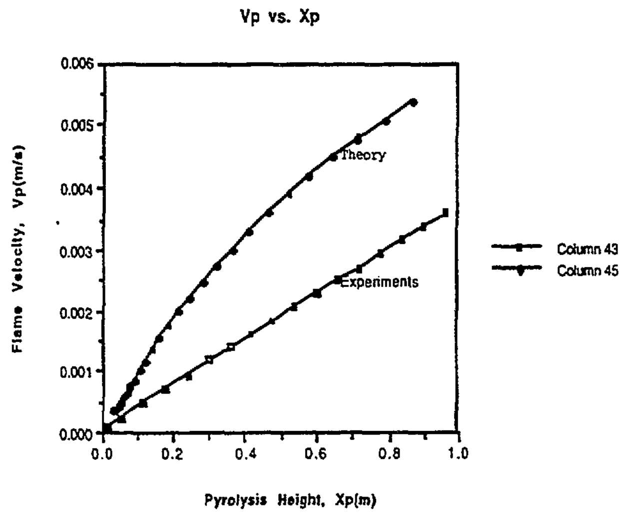
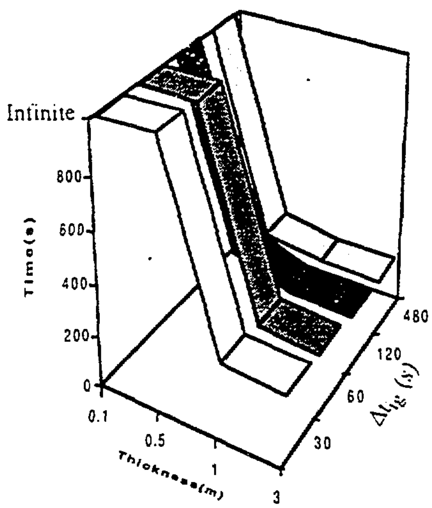


Figure 1. Comparison of Theory with experiment of Orloff et al. [3].



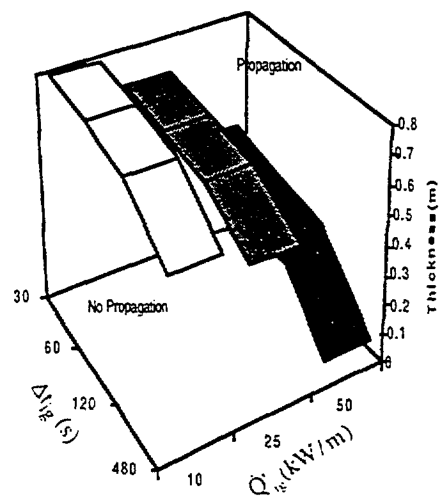


Figure 2. Time to reach 5 m as a function of material thickness and ignitor duration at 25 kW/m for the ignitor.

Figure 3. Estimated critical values for propagation to 5 m.